Madison River and Splits

Enhanced Hydraulic Analysis and Floodplain Mapping Report

Madison and Gallatin Counties, MT

May 2020

Michael Baker INTERNATIONAL

Madison River and Splits Enhanced Hydraulic Analysis and Floodplain Mapping

Madison and Gallatin Counties, MT

Prepared For:

Montana Department of Natural Resources and Conservation

Prepared By:

Michael Baker International

Document History

Document Location

Location

Revision History

Version Number	Version Date	Summary of Changes	Team/Author
01	03/02/2020	Initial Submittal of Combined Hydraulic and Floodplain Mapping	R. Anderson
02	4/23/2020	Response to Montana DNRC and Compass review comments	R. Anderson
03	5/19/2020	Revision to work maps	R. Anderson

Client Distribution

Name	Title/Organization	Location

Cover Photograph:

Madison River near Norris Road by Elk Creek.

Cover Photograph Credit:
Morrison-Maierle, Inc.

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LICENSED
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1. Introduction and Background

As part of a Mapping Activity Statement (MAS) contract initiated by the Montana Department of Natural Resources and Conservation (DNRC), Michael Baker International has completed detailed hydraulic analyses of the Madison River in Madison and Gallatin Counties, Montana. The purpose of this report is to document the hydraulic analyses and to provide results for subsequent floodplain mapping analyses. Results of the analyses will be incorporated into the Madison and Gallatin County, MT, and Incorporated Areas Digital Flood Insurance Rate Maps (DFIRMs) and Flood Insurance Study (FIS) (**References 1 and 2**). **Appendix A** includes the Certification of Compliance form that confirms the study has been completed using sound and accepted engineering practices and is in compliance with all contract documents.

A list of primary flooding sources included in this hydraulic study is provided in **Table 1-1**, and a map showing these flooding sources is provided in **Figures 1-1, 1-2, and 1-3**. It should be noted that these primary flooding sources are not the only flooding sources included in this study. Several flows split from these flooding sources to form secondary flooding sources. These split flows are detailed in **Section 3** of this report. This study represents a new study within the project area and represents two separate reaches on each side of Ennis Lake (note that Ennis Lake and the Madison River immediately below Ennis Lake are not part of the study area). The first reach ("below Ennis Lake") extends from a point 10.5 miles below Ennis Lake downstream to immediately above the Climbing Arrow Road crossing above the community of Three Forks. The second reach ("above Ennis Lake") extends from Ennis Lake upstream to above the US Highway 287 road crossing. Effective floodplain mapping for the Town of Ennis primarily emphasizes detailed mapping of the Moores Creek flooding source, the mapping does include a small sliver of approximate (Zone A) mapping within the Town boundary on the left (west) overbank bank of the Madison River. The Zone A mapping along the Madison River presented in the current effective floodplain mapping is derived from historic FEMA mapping dated November 19, 1986. The Moores Creek study is a detailed study with Base Flood Elevations and Floodway, and begins approximately 0.7 miles upstream from the Ennis town limits, extends through Ennis to approximately 0.7 miles downstream from the Ennis town limits.

The new study documented in this report includes the below Ennis Lake reach, with about 22 miles of 1D enhanced (no floodway) analyses to the upstream study limits at the mouth of Beartrap Canyon where MT Highway 84 diverges from the Madison River towards Norris, MT (**Figure 1-1**). The hydraulic analysis was completed using peak discharges for the 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance (10-, 25-, 50-, 100-, and 500-year) flood events, as well as the 1-percent-plus-annual-chance event. The above Ennis Lake reach has 4.3 miles of two-dimensional (2D) enhanced analyses (no floodway) between Ennis Lake and the Town of Ennis, approximately 2.6 miles of one-dimensional (1D) enhanced analyses with floodway at the Town of Ennis, about 9.3 miles of 2D enhanced analyses (no floodway) upstream (South) of the Town of Ennis, and about 35.5 miles of 1D enhanced (no floodway) analyses to the upstream study limits just above the MT Highway 87 bridge near Earthquake Lake (**Figures 1-2 and 1-3**).

Table 1-1: Flooding Sources Studied

Flooding Source	Upstream Limit	Downstream Limit	Reach Length (Miles)
Madison River River (below Ennis Lake)	Approximately 10.5 miles below Ennis Lake at the mouth of Beartrap Canyon	Immediately upstream of Climbing Arrow Road	22
Madison River River and Splits (above Ennis Lake)	Approximately 4,150 feet upstream of the MT Highway 87 Bridge near Earthquake Lake	Confluence with Ennis Lake	51.7

For this project, multiple contractors were involved in the delivery of the many components that comprise the Technical Support Data Notebook (TSDN). Morrison-Maierle, Inc. completed the field surveying tasks for all flooding sources in the project area (**Reference 3**). The Morrison-Maierle tasks included the collection of cross-section bathymetric survey data and hydraulic structure data. The topographic data collection was provided by Quantum Spatial (**Reference 4**). Michael Baker International (Baker) completed the hydrologic analyses for basins in the Madison River watershed (HUC 8) (**Reference 5**). The topographic, field survey, and hydrologic data were reviewed and approved by FEMA during the process of the hydraulic and floodplain mapping analyses. Detailed information regarding Morrison-Maierle, Quantum Spatial, and Baker contributions to the TSDN are included in the appropriate sections of this report.

1.1. Community Description

The study area is located in southwest Montana within Madison and Gallatin Counties and is bordered by Beaverhead County to the west and south; Silver Bow County to the northwest; Jefferson, Broadwater, and Meagher Counties to the north; Yellowstone County to the east; and Fremont County (Idaho) to the southeast. The Town of Ennis is the largest community in Madison County and Bozeman is the largest city in Gallatin County. Ennis is located along the Madison River just above Ennis Lake. Except for Ennis, there are no other cities, towns, or incorporated communities within the study area, and development is limited to relatively large, individual, sparse parcels generally located on terraces or high benches overlooking the river corridor and floodplain.

Madison and Gallatin Counties have experienced moderate- to substantial population growth in the past 18 years. **Table 1-2** summarizes the Census population data (**Reference 6 and Reference 7**). **Table 1-3** summarizes the census housing unit estimates (**Reference 5 and Reference 6**). There has been significant growth in the population since 2000 with increases in population of 44,045 and 1,917 for the Gallatin County and Madison County, respectively, between 2000 and 2018 (**Reference 8 and 9**). The Town of Ennis population increased by 157 over the same period. There has been more significant growth in the number of estimated housing units in Gallatin County and Madison County since 2000 with an additional 21,522 units (Gallatin County) and 2,328 units (Madison County) added between 2000 and 2018. Ennis added 45 units over the same period. With the availability of improved terrain data, hydraulic modeling capabilities, and an additional 35 years of hydrologic data, a study of the Madison River is warranted and will provide the local communities with a current representation of flood risk within their community. This study will help to understand the impacts on living and working near the Madison River, as well as the potential flood impacts on the physical assets of the community.

Table 1-2: Census Population Estimates

Community	2000 Population	2010 Population	% Increase from 2000 to 2010	2018 Population Estimate	% Increase from 2010 to 2018
Gallatin County	67,831	89,513	32.0%	111,876	25.0%
Madison County	6,851	7,691	12.3%	8,768	28.0%
Ennis	840	838	0.0%	997	18.7%

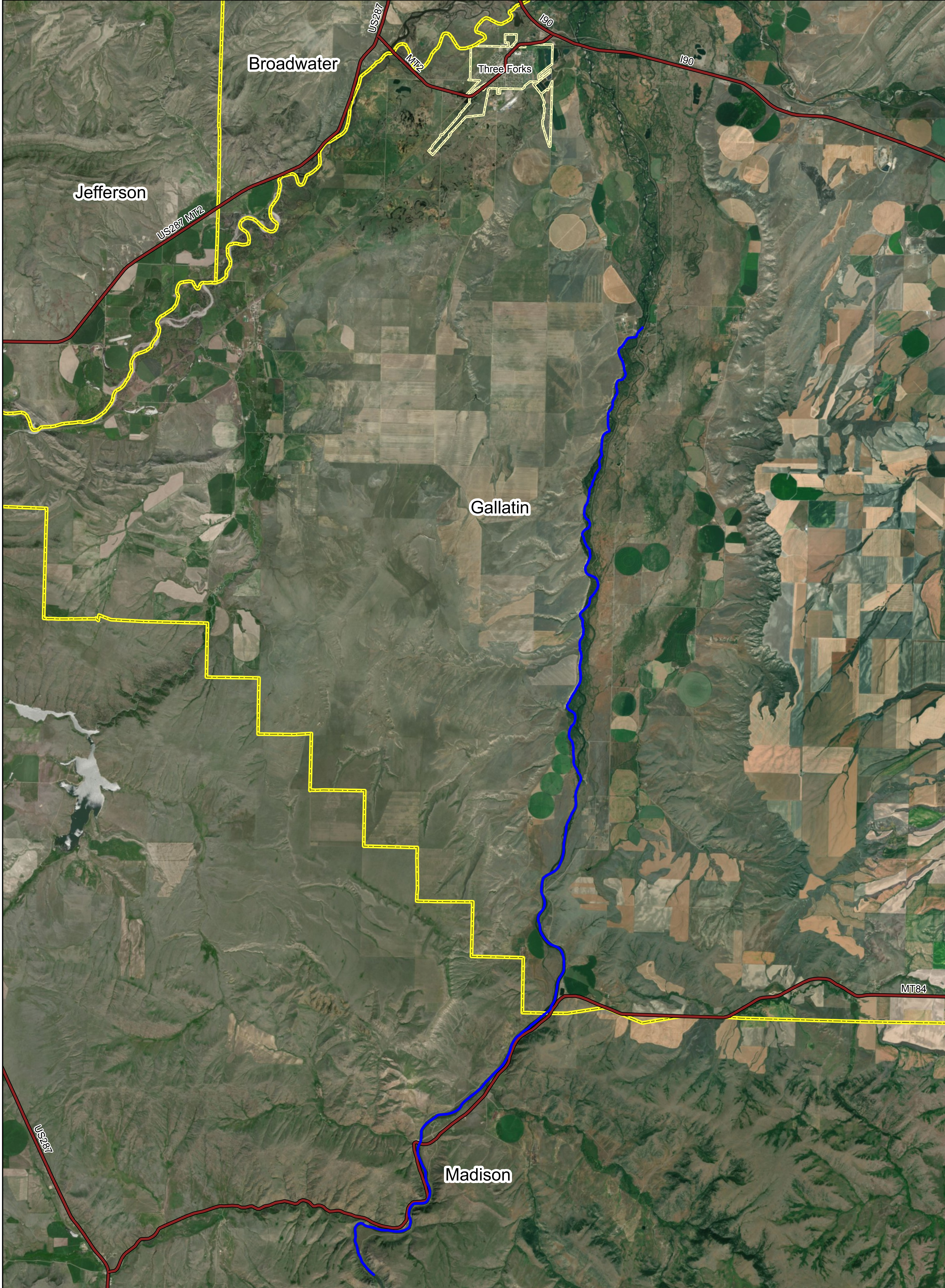
Table 1-3: Census Housing Units Estimates

Community	2000 Housing Units	2010 Housing Units	% Increase from 2000 to 2010	2018 Housing Units Estimate	% Increase from 2010 to 2018
Gallatin County	29,489	42,289	43.4%	51,011	20.6%
Madison County	4,671	6,940	48.6%	7,017	50.2%
Ennis	434	527	21.4%	479	10.4%

Most severe flooding events in the Madison River watershed (HUC 8 10020007) have been the result of spring snowmelt or ice jams. Historically, notable flooding within this watershed has occurred numerous times. Ice jamming occurs at the US Highway 287 road crossing at the Town of Ennis (upstream of this study area and above Ennis Lake, resulting in overbank flows, as does ice jamming at other more isolated locations along the Madison River. However, due to the location of the jams and the lack of development in the adjacent floodplain, ice jamming results in little to no damage.

Within or above the study area are three significant impoundments: 1) Ennis Lake, a reservoir formed by Madison Dam on the Madison River just below the town of Ennis, MT, owned by Northwestern Energy, and initially closed in 1901, 2) Hebgen Lake which is an impoundment created in 1914 and nearly nine miles above the study area and stores and regulates flows for downstream water users and power generation, and 3) Earthquake Lake, an impoundment immediately below Hebgen Lake which was created by a landslide caused by the 1959 Hebgen Lake earthquake.

Updated Flood Frequency Analyses were performed for stream gages in the study area, which utilized Bulletin 17c flood frequency analysis methods and applied record extension methods (Maintenance of Variance Extension Type III (MOVE.3)) for the analyses (**Reference 10**). Two active USGS gaging stations are located on the Madison River (USGS 06040000 Madison River near Cameron MT and USGS 06038800 Madison River at Kirby Ranch nr Cameron MT). The highest gaged peak flows at the Cameron, MT gage were almost 2% annual chance flow (8,830 cfs in 1970), with several other peak flows just under the 10% annual chance flood (6,670 cfs and 6,600 cfs in 1952 and 2011, respectively). At the stream gage near Kirby Ranch, the three highest peak flows were between the 10% and 4% annual chance floods (5,030 cfs, 5,000 cfs, and 4,840 cfs in 1993, 1986, and 1996, respectively). There are two historic USGS gaging stations within the study area (USGS 06042000 Madison River below Cherry Creek near Norris, MT and USGS 06041500 Madison River near Norris, MT) and one historic gage located immediately below the study area (below Climbing Arrow Road USGS 06042500 Madison River near Three Forks, MT). The two gages near Norris were only operated for 11 and 20 years, respectively, with their period of record beginning in the 1890's and ending in early 1900's. Thus, neither of these gage records were used in the updated Flood Frequency Analyses. The Three Forks gage has a much longer period of record (57 years; 1893 to 1950) and was included in the Flood Frequency Analysis update. The results are reported in the 2018 Baker Hydrologic report (**Reference 5**). At the Three Forks gage, the highest gaged peak flow was nearly a 4% annual chance flow (8,175 cfs in 1896), with other peak flows between the 4% annual chance flow and near the 10% annual chance flood (9,840 cfs, 6,980 cfs, and 6,650 cfs in 1943, 1894, and 1942, respectively). At the stream gage near Norris, the three highest peak flows were around the 1% and 4% annual chance floods (10,300 cfs, 8,325 cfs, and 8,000 cfs in 1899, 1901, and 1898, respectively). Stream gage locations, watershed delineations, and flow recommendations are provided in **Appendix D**.



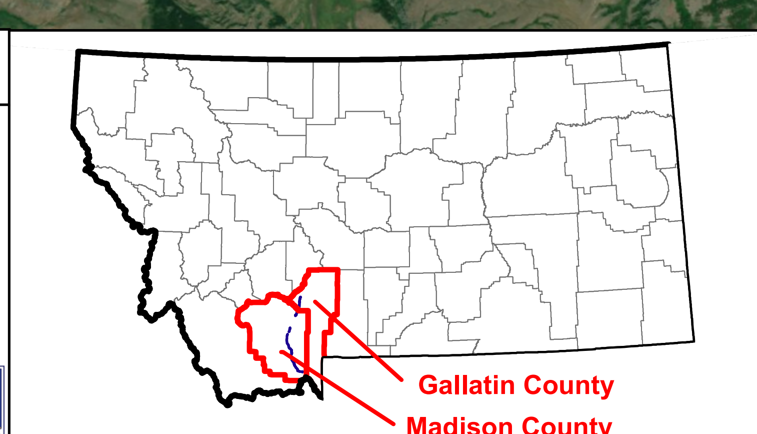


Figure 1-1: Project Area - Madison River below Ennis Lake

DATA FRAME PROPERTIES:
Coordinate System: NAD 1983 2011 StatePlane Montana FIPS 2500 Ft Int
Projection: Lambert Conformal Conic
Datum: NAD 1983 2011
Vertical Datum: NAVD 88
Units: Feet

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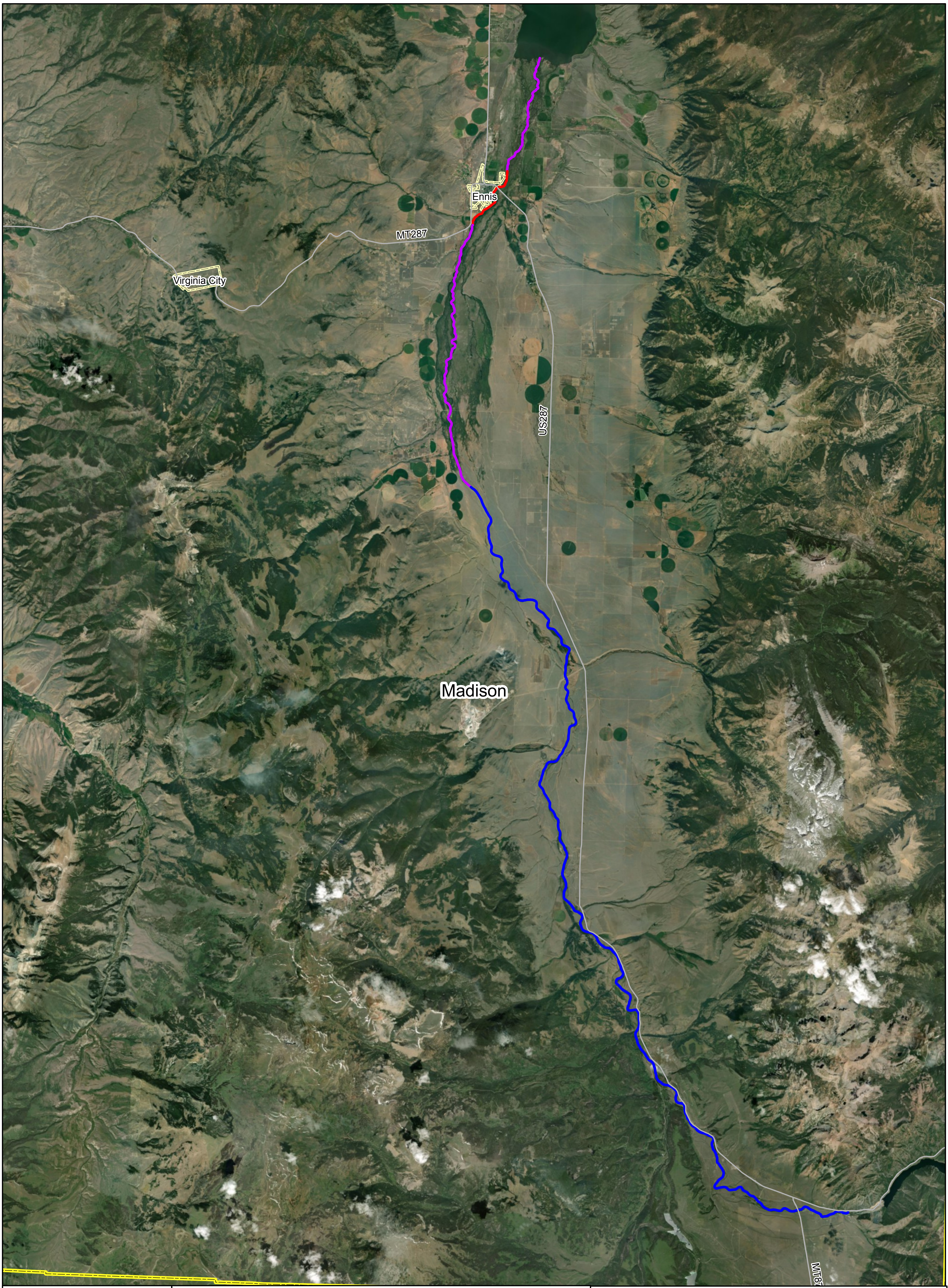
MADISON COUNTY MONTANA



Legend

- Montana_Highways
- U/S Ennis Enhanced, No FW (1D)
- U/S Ennis (2D)
- Ennis Enhanced with FW (1D)
- D/S Ennis (2D)
- Counties
- MontanaIncorporatedCitiesTowns

Figure 1-2: Project Area Flooding Source

0 0.5 1 2 3 4 Miles

DATA FRAME PROPERTIES:
Coordinate System: NAD 1983 2011 StatePlane Montana FIPS 2500 Ft Int
Projection: Lambert Conformal Conic
Datum: NAD 1983 2011
Vertical Datum: NAVD 88
Units: Feet

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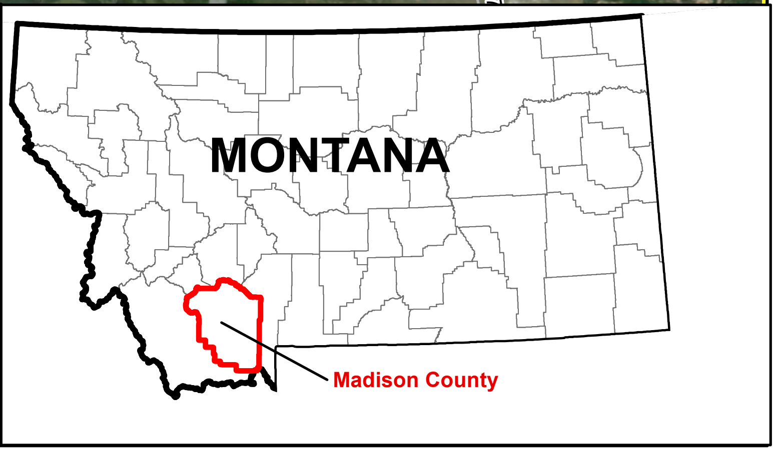
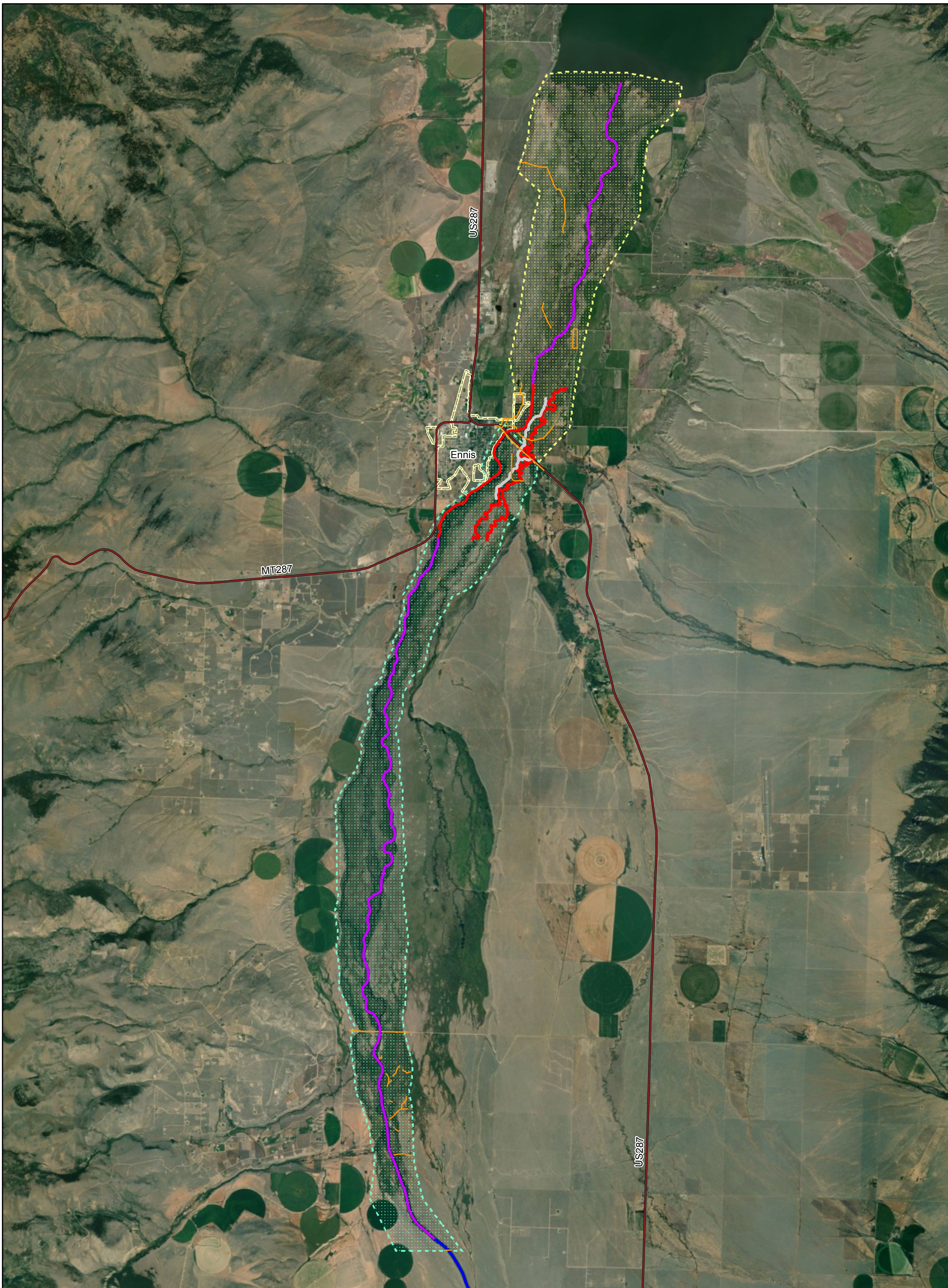
MONTANA

MONTANA DNRC





Legend

- Cities / Towns
- Montana Highways
- U/S Ennis Enhanced, No FW (1D)
- U/S Ennis (2D)
- Ennis Enhanced with FW (1D)
- D/S Ennis (2D)
- 2D Flow Area Boundary South
- 2D Flow Area Boundary North
- Flow Area Breaklines
- Lateral Structures

Figure 1-3: Ennis Area Study Reaches (1D and 2D)

Miles

0.5 0.25 0 0.5 1 1.5

DATA FRAME PROPERTIES:

Coordinate System: NAD 1983 2011 StatePlane Montana FIPS 2500 Ft Int

Projection: Lambert Conformal Conic

Datum: NAD 1983 2011

Vertical Datum: NAVD 88

Units: Feet

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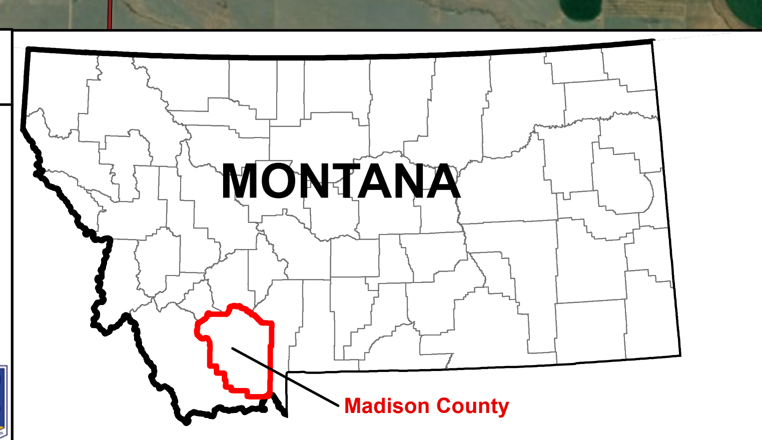

1.2. Basin Description

As reported in the 2018 Baker hydrology report (**Reference 5**), the Madison River watershed drains a substantial portion of southwest Montana and includes portions of northwest Wyoming in Yellowstone National Park. Along with the Jefferson and Gallatin Rivers, the Madison River is one of the three headwater tributaries that forms the Missouri River near Three Forks, MT. The Madison River begins at the confluence of the Gibbon and Fire Hole Rivers in Yellowstone National Park, WY, approximately 13 miles upstream of West Yellowstone. The tributaries to the Madison River drain the continental divide in the southern portion of the watershed (Firehole River), as well as the Gravelly Range and Madison Range along the western and eastern portions of the watershed, respectively. The Madison River watershed at USGS gaging station near Three Forks, MT (USGS 06042500) drains approximately 2,516 mi^2. Within the study area, at USGS gaging station near Norris, MT (USGS 06042000), the Madison River watershed drains approximately 2,416 mi^2. And USGS gaging station near Cameron, MT (USGS 06040000) and just above Ennis, the Madison River watershed drains 1,730 mi^2.

Figure 1-4: Madison River at MT Hwy 87 Bridge near upper study limit

Figure 1-5: Madison Split 1 at US Highway 287 bridge at Ennis

Along the extents of the study area defined by a profile baseline developed for this hydrologic analysis (near the outlet of Earthquake Lake by the Madison County – Gallatin County line to the confluence with the Jefferson River), the character of the Madison River varies considerably. Near the outlet of Earthquake Lake, the Madison River leaves a narrow, confined canyon formed by the Henrys Lake Mountains and Madison Range and flows into a broader valley characterized by extensive terraces on both sides of the river that confine the Madison River from near the Earthquake Lake outlet to near Ennis (approximately 35 miles). The terraces limit the lateral movement of the Madison River through this reach, which is largely single-thread, relatively straight, and has a steeper gradient than reaches of the Madison River near Ennis and Three Forks.

Figure 1-6: Madison River at Varney Rd.

Approximately nine miles above the Town of Ennis, the Madison River floodplain begins to widen, the Madison River transitions from a single thread channel to a multi-thread channel with an increasing prevalence of flow splits through the floodplain, along with the presence of seeps and springs flowing as spring creek channels fed by ground water sources. While the Town of Ennis sits largely on higher ground above the Madison River floodplain, the eastern boundary of Ennis lies adjacent to the Madison River and floodplain. Approximately five miles downstream of Ennis, the Madison River flows into Ennis Lake, a 3,850 acre impoundment formed by Madison Dam, which contains approximately 42,000 acre-ft of storage. Madison Dam was initially constructed in 1901, is currently owned by NorthWestern Energy and is operated as a hydro-electric facility. Madison Dam discharges into Beartrap Canyon, an approximately 10 mile reach of the Madison River characterized by steep canyon walls, higher gradient single-thread river, with coarse substrate including boulder-strewn rapids and minimal floodplain in overbank areas. The upper reach of the study is performed on the approximately 52 mile reach of the Madison River between Earthquake Lake and the Madison River confluence with Ennis Lake near the Town of Ennis. The lower reach portion of the study is performed on the approximately 22 mile reach of the Madison River below Beartrap Canyon to Climbing Arrow Road. Below this study reach, a separate study is being performed on the Town of Three Forks, MT, which will include the lower portions of the Jefferson River, Madison River, and below the confluence of the two on the Missouri River.

Figure 1-7: Madison River near Ennis

Figure 1-8: Madison River at MT Hwy 84 below Ennis Lake

Hebgen Lake is impounded by Hebgen Dam, completed in 1914 by Montana Power Company. Hebgen Dam is approximately 85 feet tall and provides approximately 325,000 acre-feet storage in Hebgen Lake. Hebgen Dam is operated as a hydro-electric facility by NorthWestern Energy. Earthquake Lake was formed as a result of a landslide triggered by the August 1959 magnitude 7.5 earthquake along the Madison Fault near Hebgen Lake. The US Army Corps of Engineers have performed various projects to improve stabilization of the debris that forms Earthquake Lake. As a result of a natural geologic event, there are no flow control mechanisms out of Earthquake Lake, with stabilization efforts focused primarily on the outlet of Earthquake Lake. Concern about erosion through and downstream from the Earthquake Lake spillway resulted in operational limitations on flows into Earthquake Lake (Hebgen Dam outlet) to limit Madison River flows below Earthquake Lake at USGS Gage 06038800 (Madison River at Kirby Ranch near Cameron, MT) to 3,500 cfs. However, flood events of 1993, 1996, and 1997 exceeded this threshold.

Figure 1-9: Madison River at MT Highway 84 bridge

Much of the land along the Madison River and its tributaries is in private ownership; primarily as farms, ranches, and the businesses and residents of the communities along the rivers. Throughout the remainder of the watershed, however, most of the land ownership is public land - managed primarily by the US Forest Service, Bureau of Land Management, and State of Montana.

Figure 1-10: Madison River along MT Highway 84 near Elk Creek.

The Madison River watershed elevation ranges from just over 4,000 feet above MSL (NGVD29) at the confluence with the Jefferson River, to approximately 4,160 feet at USGS gaging station 06042500 (Madison River near Three Forks MT), and over 11,000 feet in the watershed's mountain peaks. The mean basin elevation is 7,115 feet, and 76% of the basin is at an elevation above 6,000 ft. Approximately 41% of the watershed is forested. Annual precipitation varies widely across the watershed, with up to 50 inches per year in the high mountains and as low as 12 inches per year at the Madison River valley floor. Based on data collected using USGS StreamStats (**Reference 10**), mean annual precipitation averaged across the watershed is 28.7 inches per year. Temperatures vary widely across the watershed as well, with wintertime low temperatures frequently dropping well below zero degrees Fahrenheit, and summertime high temperatures average more than 80°F in the watershed's lower elevations (Montana Climate Office).

1.3. Previous Studies

Limited information is available regarding the flood risk from the Madison River in this study reach which includes Madison and Gallatin Counties. As noted previously, Moores Creek was studied within, and immediately adjacent to the Town of Ennis, but other than Approximate Zone A along very small portions of the left Madison River floodplain, the Moores Creek study did not include useful information about the Madison River (**Appendix C; Reference 1**). More detailed analyses of the Madison River have been performed in the lower reaches of the Madison River in Gallatin County near the City of Three Forks.

2. Hydrologic Analysis

Hydrologic analyses for the primary flooding sources on the Madison River watershed were documented in a 2018 hydrologic analysis reported by Baker (**Reference 5**). Discharges for the 10-, 4-, 2-, 1, 0.2, and 1 percent 'plus'-annual-chance flood events were established for use in the hydraulic analysis. The hydrologic analysis included a recommendation for the discharges that should be used in the hydraulic model. The watershed work maps from the hydrology reports are included in **Appendix D**.

A summary of discharges from the hydrologic reports is presented in **Table 2-1**.

Table 2-1: Discharges Recommended from Hydrologic Analyses

Flooding Source and Location	Peak Discharges (cfs)					
	10-Percent	4-Percent	2-Percent	1-Percent	0.2-Percent	1-Percent 'plus
Madison River Confluence with Jefferson River (Node 100)	7,529	8,694	9,517	10,298	12,000	13,226
Madison River near Three Forks, MT (USGS Gage Station 06042500)	7,440	8,600	9,420	10,200	11,900	13,100
Madison River above Elk Creek (Node 200)	7,392	8,543	9,350	10,117	11,804	12,708
Madison River below Ennis Lake, near McAllister, MT (USGS Gage Station 06041000)	7,290	8,420	9,200	9,940	11,600	11,900
Madison River near Cameron, MT (USGS Gage Station 06040000)	7,050	8,290	9,160	10,000	11,900	12,800
Madison River above Indian Creek (Node 300)	6,398	7,542	8,353	9,139	10,934	11,769
Madison River at Kirby Ranch, near Cameron, MT (USGS Gage Station 06038800)	4,550	5,410	6,040	6,660	8,120	8,760
Madison River below Hebgen Lake, near Grayling, MT (USGS Gage Station 06038500)	3,420	3,980	4,400	4,830	5,840	6,050
Madison River near West Yellowstone, MT (USGS Gage Station 06037500)	1,970	2,270	2,480	2,700	3,210	3,090

Several flow splits occur in the floodplain around the Town of Ennis. Thus, the flow changes and values for each mapped flooding source as they were determined and applied in the hydraulic model is provided in **Section 3.3** and in the Flow Diagram Maps presented in **Appendix E**.

3. Hydraulic Analysis

3.1. Methodology and Hydraulic Model Setup

Hydraulic modeling was performed using HEC-RAS version 5.0.7 (**Reference 11**). One-dimensional (1D) and two-dimensional (2D) modeling was performed for the analyses in this study area. For 1D modeling, cross sections were cut and terrain data was transferred from GIS using CivilGEO's GeoHECRAS software (**Reference 12**). All culverts, bridges, and inline structures were modeled in accordance with the HEC-RAS User's Manual, Version 5.0 (**Reference 13 and Reference 13**). In addition, standards listed in FEMA's Knowledge Sharing Site (KSS) (**Reference 15**) were followed to ensure the study meets industry standards. 2D modeling was performed using terrain data derived from Light Detection and Ranging (LiDAR) topographic data collection by Quantum Spatial in fall 2017 and documented in Madison River, Montana LiDAR Technical Data Report (**Reference 4**) were used in the analysis.

Four sets of models were created for this study. One set of models were the 2D hydraulic models developed for the Madison River and floodplain in the study reach beginning above Ennis Lake to above the Town of Ennis. These models were used to provide hydraulic analysis results for the study reaches above and below the Town of Ennis. A second set of models were developed to perform an enhanced hydraulic analysis on a 2.6 mile reach of the Madison River at the Town of Ennis. These models are 1D models and include floodway analyses on this Ennis reach of the study. The 1D models were set up and used the results of the 2D analyses to establish split flow paths and flow values for the 1D analyses. A third set of models were developed to perform the hydraulic analyses (enhanced, no floodway) above the Town of Ennis to the upper extent of the Madison River floodplain study immediately above the US Highway 287 bridge near Earthquake Lake. While the three sets of modeling varied based on the analysis methods and output, they all are linked by a stream channel centerline that begins at the confluence with Ennis Lake and ends at the upper study limit. The fourth set of models were used for the reach below Ennis Lake downstream to Climbing Arrow Road. The base map terrain data spans the entire study reach and continuous and connected water surface profiles and floodplain extents along the above and below Ennis Lake study reaches.

Detailed information on floodway modeling can be found in **Section 3.14** of this report. **Appendix B** contains the Hydraulic Work Maps and **Appendix E** contains the Flow Diagram Maps.

3.2. Field Survey and Topographic Information

Field survey and topographic information were collected using the methods and procedures outlined in FEMA's Guidelines and Specifications for Flood Risk Analysis and Mapping. Specifically, FEMA's Data Capture Technical Reference (**Reference 16**), Guidance for Flood Risk Analysis and Mapping Data Capture - General (**Reference 17**), and Guidance for Flood Risk Analysis and Mapping Data Capture – Workflow Details (**Reference 18**) were adhered to.

3.2.1 LiDAR Collection

Terrain data was collected in October and November, 2017, for the entire study footprint area in the form of LiDAR points by Quantum Spatial (**Reference 4**). The LiDAR deliverables included digital elevation models (DEM) (3.0 ft resolution), 1.0 ft contours, and a report documentation among other items.

The LiDAR DEM (3.0 ft resolution) was the primary topographic source for the project and was used, in addition to collected field survey, to develop the HEC-RAS cross-sections.

3.2.2 Field Survey Collection

Bathymetric data collection was necessary to supplement the LiDAR data since the streams are detailed study reaches which require a higher level of data inputs to achieve better modeling results. Detailed hydraulic analyses also require that all structures be included in the modeling unless it can be shown that the structure is not hydraulically significant to the model results. Therefore, field survey was collected.

Ground survey was collected for select riverine cross sections and all hydraulic structures between October 2018 and January 2019 by Morrison-Maierle (**Reference 3**). Supplemental field survey at select locations was performed in May 2019. Survey data was collected using GNSS RTK methods of survey. Additionally, a Trimble S6 Robotic Total Station was used to collect data at select locations where GPS signal could not be acquired. A SonarMite single beam echo sounder was used in conjunction with the GNSS RTK rover to map deeper portions of the Madison River where wading was impractical. Within the Town of Ennis enhanced (with floodway) study reach, channel cross-sections were taken at approximate maximum 1,000 foot intervals. In total, for the lower reach, nine bathymetric cross-sectional field surveys were performed within the study reach, and three additional cross sections were surveyed adjacent to the study area to characterize the channel characteristics below the water surface. One structure was surveyed in the lower reach. For the upper study reach, 74 cross sections and 13 structures were surveyed. **Table 3-1** lists the number of cross-section and structure surveys that were completed for the study reach.

The field survey data was presented in Montana State Plane 2500 coordinates, North American Datum of 1983 (NAD83-2011). Units are reported in International Feet. Elevations are referenced to the North American Vertical Datum of 1988 (NAVD88). Units are reported in U.S. Feet. GNSS-derived orthometric heights (elevations) were computed using Geoid 12B.

In addition, photographs and sketches of the hydraulic structure was taken to assist with the creation of the hydraulic model cross-section geometries. These photographs are included in **Appendix F** of this report. All surveyed hydraulic cross sections and structures were incorporated into the hydraulic model.

Table 3-1: Field Survey Collection Summary

Flooding Source	Number of Hydraulic Structures	Number of Cross Sections
Madison River (below Ennis Lake)	1	9
Madison River and Splits (above Ennis Lake	13	74

3.3. Flow Areas

This study involves 1D and 2D hydraulic analyses within the study area to best describe and represent the flood risks in these areas. 1D study methods were utilized in locations where encroachment analyses were performed to establish the regulatory floodway. 1D study methods were also utilized in the uppermost study reach above the Town of Ennis where a well-defined, single-thread, meandering channel exists within a relatively confined river corridor that lacks a broad, extensive floodplain that is present in other reaches of the Madison River (e.g. near the Town of Ennis). 1D study methods were utilized in the reach below Ennis Lake. 2D hydraulic analyses were performed in Madison River reaches with broad, extensive floodplains with flow patterns that result in multiple flow splits and interactions between flow splits and mainstem Madison River. The below Ennis Lake study area (1D) is presented on **Figure 1-1**. The above Ennis Lake study areas (1D and 2D) are presented in **Figures 1-2** and **1-3**.

3.3.1 1D Flow Areas

Cross sections were extracted from DEMs derived from LiDAR data and modified to represent bathymetric conditions below the water surface. Cross sections were placed at all field survey locations within the 1D study areas and the field survey data were directly input into the cross section geometry. Cross sections were generally placed with 300 ft spacing, with closer cross section spacing in areas of more complicated flow patterns and where there are significant interactions between mainstem Madison River flows and split flow channels. Cross sections were placed at all road crossing in accordance with the four cross section layout described in the HEC-RAS Hydraulic Reference Manual. The upstream and downstream cross sections for the US Highway 287 bridge at Ennis are placed within the roadway embankment zone because those were the locations of the field survey data collection provided by the survey contractor. It does not appear that these cross section locations are likely to change the results of hydraulic analyses through the structure. Expansion and contraction coefficients of 0.3 and 0.5 were applied to the three uppermost cross sections of the standard four bridge cross section layout (cross sections 2, 3, and 4) per the HEC-RAS Hydraulic Reference Manual.

3.3.2 2D Flow Areas

2-D flow area grids were established for the 13.6 mile reach of the Madison River in the vicinity of Ennis. The 2D study area was divided into two sub-areas: 1) a 9.3 mile segment of the Madison River and floodplain south of the US Highway 287 bridge at Ennis, and 2) a 4.3 mile segment of the Madison River and floodplain north of the US Highway 287 bridge at Ennis. The grid areas associated with the 2D flow areas are 7.7 square miles (south) and 3.4 square miles (north). Typical grid cells were set with an average dimension of 25 feet by 25 feet. The grid was further refined using breaklines, to more appropriately account for and model topographic breaks on road embankments, significant channel banks, and other significant topographic features which had the likelihood of impacting hydraulic conditions.

At the two road crossings in the 2D study area (US Highway 287 at Ennis and Varney Road south of Ennis), bridge pier information from the structure survey was input into the model domain and grid cell dimensions were refined to better represent the hydraulic conditions through the crossings. The resultant water surface elevations were verified to be below the road crossing low-chord elevation, thus pressure flow and weir/overtopping flow analyses were not required. Additionally, the resulting flows through the five openings (all bridges) of the US Highway 287 road crossing at Ennis from the 2D south analysis were used as the boundary conditions for the 2D north analysis. One culvert in the 2D south study reach (on Varney Road, east of the Varney bridge) was identified as having the potential for significant flow distribution in the right overbank floodplain and was input into the 2D flow domain using culvert routines. Model results indicated flows through this culvert are relatively insignificant (less than 5 cfs), however the model configuration with flow through the culvert was utilized for the analysis.

3.4. Split Flow Analysis

Due to the limited capacity of the primary flooding sources, there are numerous split flows that leave main channels and become flooding sources unto themselves. Some splits only leave during extreme flood events, but others can be expected with some regularity. Each flow where a significant amount of flow would leave the main channel was modeled. (Flow may split in other locations, but will likely be either low discharge or less than 0.5 feet deep). The magnitude of each of the split flows was calculated in HEC-RAS models separate from the regulatory models. **Table 3-2** lists each of these split flows, which flooding source each splits from, and in which model the calculation was made.

Table 3-2: Split Flow Descriptions

Split Flow Name	Splits from	Model Project/Plan	Stream Length (miles)
Madison Split 1	Madison River	Madison River Ennis/ Multiple Opt Upstream and Multiple Opt Downstream	4.3
Madison Split 2	Madison River	Madison River Ennis/ Downstream Opt	1.1
Madison Main St	Madison Split 1	Madison River Ennis/ Multiple Opt Upstream	0.3

The flow rates for Madison Splits 1 and 2 were developed based on the 2D hydraulic analyses performed immediately upstream of this study reach. The flow rates for Madison Main St were calculated using the lateral weir function within HEC-RAS. Lateral weir coefficients were carefully selected based on guidance for values recommended by HEC in the document "HEC-RAS 5.0 2D Modeling Users Manual". In general, the weir coefficient values in the hydraulic model correlate to the height and shape of the weir and fall into the ranges given in **Table 3-3**.

Some of the flow calculation model runs produce the HEC-RAS warning, "Flow Optimization Failed to Converge" for certain profiles. This is a common warning for HEC-RAS models with multiple optimized lateral weirs. In these cases, the flow calculations were closely examined to ensure that the model is stable and producing reasonable results that are near convergence.

The network of split flows did change the magnitude of peak discharges for the Madison River flooding sources. Therefore, the discharge values from the hydrologic analyses were modified in the Town of Ennis reach to account for the impacts of the split flows. The table titled "Cross Section Discharge and Elevation Table" in **Appendix H** contains the correct flooding discharges as modified by the hydraulic split calculations. The flow diagram that illustrates these splits is provided in **Appendix E.**

Table 3-3: Lateral Weir Coefficients

Description	Weir Coefficient Range
Levee/Roadway – 3 ft or higher above natural ground, broad crested weir shape, flow over levee/road acts like weir flow	1.5 to 2.6
Levee/Roadway – 1 to 3 ft elevated above ground, broad crested weir shape, flow over levee/road acts like weir flow but becomes easily submerged	1.0 to 2.0
Natural high ground barrier – 1 to 3 ft high, does not really act like a weir, but water must flow over high ground to get into 2D flow area	0.5 to 1.0
Non elevated overbank terrain – lateral structure not elevated above ground	0.2 to 0.5

3.5. Profile Baseline

The centerlines for all flooding sources of the Madison River was used to define the Profile Baselines and river stationing. For the lower reach, the stream stationing for the Madison River references the stream distance in feet above the Climbing Arrow Road bridge. The lower reach HEC-RAS model uses River Stationing and establishes the lower-most cross section as River Station 1000. Thus, there is a difference of 890 feet between River Stationing (HEC-RAS Cross Sections) and the reported distance in feet above Climbing Arrow Road bridge. The Hydraulic Analysis Tables in **Appendix H** provide a cross reference between River Stationing (in feet above Climbing Arrow Road bridge) and Cross Section stationing in the HEC-RAS model. The upper reach stream stationing begins at the confluence with Ennis Lake. **Table 3-2** lists the stationing reference. Additional information on key features along each profile baseline can be found in tables in **Appendix H**.

Table 3-4: Summary of Station References (by reach)

Flooding Source	Station Reference
Above Ennis Lake Reach	
Madison River	Feet above limit of study (Confluence with Ennis Lake)
Madison Split 1	Feet above limit of study (Split River Station 0 coincident with Madison River Station 23521)
Madison Split 2	Feet above confluence with Madison Split 1
Madison Main St	Feet above confluence with Madison Split 1
Below Ennis Lake Reach	
Madison River	Feet above Climbing Arrow Road bridge

3.6. Boundary Conditions

The below Ennis Lake reach boundary conditions were established using known depth water surface elevations at the downstream extent of the study reach taken from the model results from the Three Forks Study (in review). These water surface elevations were selected to provide continuity and proper tie-in between the two studies.

The upper reach boundary conditions were all set using either normal depth water surface elevations, known water surface elevations, or junctions with other flooding sources. For normal depth boundary conditions, the slope was calculated based on the slope of the channel in the vicinity of the most downstream cross section. For some flooding sources, water surface elevations at the downstream end of the reach will be controlled by backwater from the receiving flooding source.

3.6.1 1D Reach below Ennis Lake (Below Ennis Lake Reach)

The 1D study reach below Ennis Lake utilizes the known water surface elevations from the Three Forks study hydraulics analysis as the downstream boundary condition.

3.6.2 2D Reach Between Ennis Lake and Ennis (2D North; Above Ennis Lake Reach)

The lower study limits intersect Ennis Lake, which can vary significantly in reservoir pool elevation based on reservoir operations. Documentation provided by Northwestern Energy indicates that full pool elevation is 4,819.7 ft (NAVD 88). This elevation is consistent with photo-interpretation of aerial imagery and DEM's develop based on the 2017 LiDAR data collect. Boundary conditions based on normal depth at full pool were utilized for the hydraulic analysis, and floodplain details of the Madison River flood risk will extend below full pool elevation to provide flood risk information when the reservoir is below the lake footprint at full pool elevation. However, local floodplain officials should consider full pool elevation water surface elevations when evaluating development requests along Ennis Lake.

The upstream boundary conditions for this reach are described based on the 2D flow distributions that occur through the US Highway 287 bridge at Ennis. An abandoned roadway bed immediately downstream of the US Highway 287 bridge at Ennis provides a significant hydraulic control that redistributes flows exiting the highway bridge into two principle flowpaths: 1) mainstem Madison River, and 2) continuation of Madison Split 1 that eventually rejoins the mainstem Madison River well below the lower 2D study limits. The flow distributions were verified with the results of the split flow analyses performed in the 1D Reach at Ennis described in **Section 3.6.3** to confirm the models have good agreement. To improve model stability and computational efficiency, unsteady flows were gradually ramped up to the associated flow profile value over a 24-hour time period.

3.6.2.1 2D Model Setup

The model used a three-second timestep, with a 48-hour total simulation time. The full momentum equation setting is used.

3.6.3 1D Reach at Ennis (Above Ennis Lake Reach)

Normal depth is the downstream boundary condition utilized for the mainstem Madison River at downstream study limits and the Madison Split 1 at downstream study limits. The downstream boundary condition for the Madison Main St split is the junction with Madison Split 1 (downstream of US Highway 287 bridge). The downstream boundary condition for Madison Split 2 is the junction with Madison Split 1 (upstream of US Highway 287 bridge).

The steady flow conditions for the mainstem Madison River, Madison Split 1, and Madison Split 2 at beginning of the 1D enhanced (with floodway) study area are based on the results of the 2D analysis in the reach above Ennis (**Section 3.6.4**).

3.6.4 2D Reach above Ennis (2D South; Above Ennis Lake Reach)

Normal depth is the downstream boundary condition for the 2D hydraulic analysis in the Madison River reach upstream of Ennis. Flow distributions were determined from 2D hydraulic analysis and these were used to inform the development of and initial flow values to be used in the 1D hydraulic analyses through Ennis. Three distinct flow paths were clearly identified at the downstream extents of the 2D study reach above Ennis.

The upstream boundary condition for the 2D reach above Ennis is based on the output of the 1D enhanced analysis (no floodway) for the upper extents of the study area. The upstream extent of the 2D study area above Ennis was established to provide significant overlap with the 1D study area above Ennis. The start of the 2D study reach above Ennis is characterized by a relative deep, narrow, confined river channel that contains the 1% and 0.2% annual chance floods. Thus, the recommended flow values from the hydrologic report were input as upstream boundary conditions. To improve model stability and computational efficiency, unsteady flows were gradually ramped up to the associated flow profile value over a 20-hour time period

3.6.4.1 Model Setup

The model used a three-second timestep, with a 48-hour total simulation time. The full momentum equation set is used.

3.6.5 1D Reach above Ennis (Above Ennis Lake Reach)

The 1D study reach above Ennis to the upstream project limits utilize the known water surface elevations from the 2D reach above Ennis analysis as downstream boundary conditions. As indicated above, there is significant overlap between the 1D and 2D study reaches above Ennis to establish the appropriate conditions in this transition between the study reaches. The overlapping area is characterized by a relatively deep, narrow, confined river channel that contains the 1% and 0.2% annual chance floods within the river banks.

Table 3-3 summarizes the boundary conditions used in the analysis.

Table 3-3: Boundary Conditions

Flooding Source	Boundary Condition
Below Ennis Lake Reach	
Madison River	Downstream: Known WSE from Three Forks Study Upstream: Flows developed for the Madison River below Ennis Lake as reported in Madison River Watershed Hydrologic Analysis report
Above Ennis Lake Reach	
Madison River at Ennis Lake (2D below Ennis Reach)	Downstream: Normal Depth = 0.002582 Upstream: US Hwy 287 flow distribution
Madison River at lower reach limit (1D Ennis Reach)	Normal Depth = 0.005119
Madison Split 1 at lower reach limit (1D Ennis Reach)	Normal Depth = 0.002504
Madison Main Str Split (1D Ennis Reach)	Junction with Madison Split 1
Madison Split 2 (1D Ennis Reach)	Junction with Madison Split 1
Madison River above Ennis (2D above Ennis Reach)	Downstream: Normal Depth = 0.004744 Upstream: flow distribution
Madison River above Ennis (1D above Ennis Reach)	Known Water Surface Elevation

3.7. Manning's Roughness Coefficients

Manning's roughness coefficients (Manning's 'n' values) were determined based on aerial imagery and photographs provided by the Morrison-Maierle survey (**Reference 3**). Nine land cover designations were identified within the study reach with Manning's 'n' values ranging from 0.015 (roadways) to 0.075 (Riparian trees / brush). Manning's 'n' value for defined channels is 0.035. Manning's values were manually established based on observation of the land cover type and extent of the coverage. For the 2D study areas, land use was manually digitized based on interpretation of aerial photo imagery and assigned a land use class and associated Manning's 'n' value. 2D analyses use the roughness grid for calculations at the grid scale.

Table 3-4: Manning's 'n' Values used in Hydraulic Model

Land Use and Description	Range of Manning's 'n' Values
Channel	0.030 – 0.035
Overbanks – Agriculture	0.035 – 0.045
Overbanks – Riparian trees/brush	0.065 – 0.075
Overbanks – Developed	0.055 – 0.065
Overbanks – Riparian grass/brush	0.055 – 0.065
Overbanks – Pond	0.03 – 0.04
Overbanks – Dirt and grassland	0.03 – 0.04
Overbanks – Roadway	0.015 – 0.017
Overbanks – Grassland	0.04 – 0.05

3.8. Development of Cross-Sectional Geometries

Cross sectional geometries were established based on the geometry of both the 2017 LiDAR and the 2018 / 2019 field survey. Cross sectional geometries were extracted from the LiDAR sourced DEMs using GeoHECRAS (**Reference 12**). At locations where cross section survey was collected, the survey data was conflated on the cross section at the appropriate location using manual methods.

At cross section locations along the primary flooding sources where survey data was not collected, bathymetric cross section geometry was either interpolated between adjacent surveyed cross sections or typical channel bathymetric characteristics were burned into DEM surface and cross section geometry was extracted from this modified DEM.

For cross sections on the secondary or split flow flooding sources, cross sectional geometries were determined using the LiDAR terrain data only. Given that these flooding sources did not contain water when the LiDAR was collected (e.g. late fall low flow conditions), bathymetric or survey data would not improve the modeling geometries. Therefore, survey was not collected or used in the model for these flooding sources.

Cross section locations were set using established engineering practice and guidance provided in the HEC-RAS Hydraulic Reference Manual.

Contraction and expansion coefficients were generally set as recommended in the HEC-RAS Hydraulic Reference Manual – 0.1 and 0.3 in areas of gradual transition, 0.3 and 0.5 at typical bridge sections, and 0.6 and 0.8 at locations with abrupt transitions. An exception to typical bridge contraction and expansion coefficients is at the Madison Main Str crossing of US Highway 287 at Ennis. The channel and overbank flow characteristics through this crossing do not result in significant contraction or expansion and are represented with 0.1 and 0.3 coefficients through the crossing.

Bank stations were placed at the boundary between the stream channel and the overbank area – when possible, at a topographic inflection point which divides the stream from the overbank. Due to the unique hydrologic and hydraulic attributes of the Madison River, bank stations are higher than most typical riverine studies. In some cases, large flow events fit entirely within the stream channel of the Madison River. This unique river morphology is likely the result of reduced flow discharges over time, related to the construction of Hebgen Dam in the early 1900's and establishment of Earthquake Lake in 1959.

During the hydraulic modeling, it was noted that channel thalweg elevations occasionally created seemingly uphill ground surface gradients between cross sections in localized areas. The uphill gradient is typically not significant and is likely caused by local sediment scour and deposition.

Photographs of select cross sections (adjacent to hydraulic structures) can be viewed in **Appendix F.** The cross section numbering is based on the reach (above or below Ennis Lake) HEC-RAS river stations and not the river station the cross section was assigned when the field survey was collected. The "Surveyed Structure Stationing Key" table in **Appendix D** provides a cross walk between the HEC-RAS river stations and the survey data. In addition, a "Structures without Photographs" table was included in **Appendix F** to list the structures that do not have photographs to help identify them. Cross section geometries can be viewed in **Appendix E.**

3.9. Hydraulic Structure

The hydraulic structure was modeled in HEC-RAS using established engineering practice and guidance provided in the HEC-RAS Hydraulic Reference Manual. Fourteen structures were surveyed and modeled in the hydraulic model, all along the primary flooding sources. A summary of the structures is provided in a table in the "Summary of Modeled Hydraulic Structures" table in **Appendix H**.

Structure geometry was taken from the collected survey data. The photographs, sketches, and spatial data in GIS were all used to most reasonably and accurately model the geometry of each individual hydraulic structure.

Low flow and high flow structure modeling approach was all determined in accordance with guidance provided in the HEC-RAS Hydraulic Reference Manual.

One hydraulic structure is oriented at a skew to the principle flow path streamline and was thus adjusted for skew (including bounding cross sections) in accordance with the HEC-RAS Hydraulic Reference Manual.

Photographs of the hydraulic structure can be viewed in **Appendix F**. Structure and cross section geometries can be viewed in **Appendix E**.

3.10. Non-Conveyance Areas

Ineffective areas were used in the model to restrict flows to areas of cross sections capable of actively conveying flow. Ineffective flow areas were used to model several different hydraulic scenarios:

1. In the vicinity of hydraulic structures, ineffective areas are used in areas that would not actively convey flow due to being blocked by the abutments or the approach to the structure itself. These ineffective areas were placed in accordance with structure modeling guidance provided in the HEC-RAS Hydraulic Reference Manual.

2. For hydraulically disconnected regions, ineffective areas were added to the model to account for the fact that flow would not be actively conveyed in these areas.

3. In overbank areas where flow during flooding events would be minor or insignificant, ineffective areas were used to ensure that accurate hydraulic calculations were taking place in the active, more significant flowpaths. This type of area tended to be a location where flow would not significantly penetrate, such as locations where flow to the lower overbank areas would be mostly blocked by high ground or an embankment near to the bank station.

4. Areas of backwater were modeled as ineffective flow.

5. Areas where the flow would be predominately lateral to the primary direction of flow were modeled as ineffective flow areas. One example of this would be at a cross section where a lateral incoming ditch was picked up along the cross section from the terrain data. These areas of lateral flow would not convey flow effectively in the primary flow direction during a flooding event.

Blocked obstructions were also used in the model. These blocked obstructions primarily served two main purposes:

1. Blocked obstructions were used to block off the “normal” elevation of lakes, ponds, and other localized depressions.

2. Madison Split 1 was modeled with blocked obstruction in low lying areas or where a cross section has a place where flow would be accounted for twice.

All ineffective areas were placed in accordance with sound engineering judgment and guidance from the HEC-RAS Hydraulic Reference Manual. In total, 519 cross sections contain ineffective flow areas, blocked obstructions, or both. A summary of cross sections with ineffective areas or blocked obstruction, along with reason for the placement of ineffective or blocked areas, is contained in the table titled “Explanation of Ineffective Flows” in **Appendix H.**

3.11. Model Results and Mapping

The model appears to produce reasonable results throughout the study reach. The floodplain is broad in many areas, with many numerous primary and secondary flowpaths throughout. This is expected in these locations and reasonable given the underlying terrain and the fact that the channel is undersized relative to the magnitude of flow during the low recurrence interval, higher magnitude flow events evaluated in this study.

The resultant floodplains were exported from the model and smoothed and minimally refined using automated processes to develop hydraulic workmaps. During the floodplain mapping phase of the project, the initial results containing "raw" floodplain output were refined as described in **Section 4** and are included in **Appendix B**.

3.12. Letter of Map Revision and Existing Study Data Incorporation

No LOMRs or any other existing studies were included in this analysis.

3.13. Multiple/Worst Case Scenario Analysis

A non-certified levee exists within the below Ennis Lake study area, on the right bank/overbank areas of the Madison River at the lower end of this study reach. This non-certified levee extends approximately 5 miles upstream from the lower extent of the study at the Climbing Arrow Road bridge. The levee extends beyond this study reach into the study area currently underway for the community of Three Forks, MT. This levee is labeled Madison Levee East and this structure was studied to perform a worst-case scenario analysis for the levee. Details of the analysis are provided below, and the scenario analysis is conducted using the same methodologies as the Three Forks, MT study, currently under review.

Madison Levee East is a non-certified levee structure on the right side of the Madison River that begins approximately 5 miles upstream of the lower extents of this study boundary and continues to a short distance downstream of Interstate 90 – another 8 miles below this study limit and through a portion of the Three Forks, MT study. It is significant structure, ranging from around 8 to 10 feet in height above the surrounding terrain. If this non-certified levee were to fail, flow would move to the east of the Madison River. At some locations, the flow would be captured by a designed ditch on the landward side of the levee, or it may expand further to the east in the valley.

For this structure, with- and without- levee analyses were performed for the entirety of the levee reach. The with-levee analysis uses ineffective flow areas at the top of the levee structure in the model cross sectional geometry. This analysis can be found in the model plan titled "MadisonBelowEnnisLake w levee". The without-levee analysis allows flow to be effective in the ditch on the landward side of the levee, and can be found in the model plan "MadisonBelowEnnisLake wo levee". Water surface elevations for the without levee analysis are typically 0 to 0.9 feet lower, and should be used to map flood hazards on the landward side of the levee. On the river side of the levee, the with-levee elevations should be used. Failure of this non-certified levee is not likely to produce flow that will follow a separate flow path from the Madison River or the adjacent ditch; therefore, no separate flow calculations are necessary.

3.14. Floodway Analysis

A floodway analysis was performed for the study area at the Town of Ennis. The main channel of Madison River contains all the flow for the floodway, so floodway mapping for the flow splits are not required. Floodway for the Madison River was determined using the equal conveyance reduction method. Per state of Montana guidelines, the maximum allowable surcharge at any given cross section is 0.50 feet. The floodway encroachment stations were revised until this requirement was met.

Several notes on the equal conveyance reduction floodways:

- The encroachment stations are set using the HEC-RAS hydraulic modeling program, encroaching on the overbanks on each side of the channel by reducing the conveyance equally on both sides until the target surcharge (0.50 feet) is met.
- When HEC-RAS sets the encroachment stations after the first floodway modeling run, there are frequently surcharges greater than the maximum allowable at many cross sections. The target surcharge is lowered on a cross section-by-cross section basis until the maximum allowable surcharge is not exceeded at any cross section.
- It is generally not possible for the surcharge to be exactly 0.50 feet at all locations. The surcharge is brought as close to the maximum allowable height at each cross section without going over.
- Negative surcharges are occasionally calculated in HEC-RAS. Efforts were made to change the encroachment stationing to remove the negative surcharges.
- At some areas where cross sections are close together, the equal conveyance reduction method produces a floodway that is unreasonable due to inconsistent floodway widths between cross sections. The floodway is smoothed by manually moving encroachment stations in the model.
- Because the encroachments are not allowed into the channels of flooding sources, floodways sometimes appear to be unbalanced. However, this is appropriate: if the channel is on the far left side of the floodplain, for example, the left side cannot be further encroached and all encroaching is done on the right side of the floodplain.

3.15. Ice Jam Analysis

An ice jam analysis was performed to support the below Ennis Lake study reach. A memo detailing the ice jam analysis is provided in **Appendix L**. Guidance for Flood Risk Analysis and Mapping – Ice-Jam Analyses and Mapping (**Reference 19**) was followed for this analysis.

Historical ice-affected flooding on the Madison River near Three Forks dates as far back as 1867. Unfortunately, most of the documentation is qualitative or anecdotal. The historical stage-discharge record is limited to a consecutive nine-year period with four years having a peak annual stage that was ice-affected (USGS at Gage No. 06042500). This stream gage was located immediately below Climbing Arrow Road bridge (gage decommissioned in 1950), which is immediately below the lower extents of this study. Ice-affected flooding on the Madison River has historically occurred during the winter months, between December and March. Flooding is the result of winter ice gorging, a process by which the channel becomes choked by the development of frazil ice and anchor ice over an extended period of extreme cold weather. Ice gorging typically occurs over long river runs; in excess of 10 miles. Ice gorging can either reduce conveyance area of the channel(s) and floodplains by the local development of ice (identified in this analysis as ice gorging), or it can be transported downstream and subsequently accumulate on fixed ice cover or at hydraulic constrictions (identified in this analysis as freezeup jams).

Effective mapping of the Madison River in the Three Forks area (there is no effective mapping in this study reach) is based on indirect methods of ice jam modeling performed by Van Mullem in 2004 (**Reference 20**). The Three Forks, MT study attempted to update the ice jam modeling using HEC-RAS for the entire Madison River reach with the intent of applying the model technique to this study reach. However, a reasonable ice jam model could not be developed and there is insufficient support for the methods and assumptions used to develop the Van Mullem model. It was determined that the equations used to model breakup ice jams in HEC-RAS are not suited to modeling the development and distribution of ice gorging or freezeup jam conditions on the Madison River.

Direct methods were used to develop an adjusted ice-affected rating curve at the Madison River gage station using the nine years of historical gage data collected between 1942 and 1950. The direct analysis clearly indicates that the ice-affected stage can be significantly higher than open water stages on the Madison River. Current FEMA guidance indicates that Mapping Partners will usually not be required to address freezeup-type jams when performing enhanced studies, other than when possible exceptions exist (**Reference 19**). The direct analysis indicates that the Madison River in this study area is such an exception, because the ice jam occurrence during low magnitude flows can yield water surface elevations substantially higher than open water 1% annual chance conditions.

However, the period of record at the gage does not satisfy the requirements that make the direct analysis the preferred approach. Given unreasonable profiles and ice thicknesses modeled by the indirect analysis, and lack of confidence in the model results, the direct analysis is the preferred approach for this study. Further detailed discussion of reasoning and defense for this determination are presented in **Appendix L**.

Other nearby gages were reviewed in order to identify possible trends in ice-affected stage (geographically and with extended periods of record) that would support use of the direct analysis of the Madison River gage near Three Forks, MT (at Climbing Arrow Road bridge). The comparative analysis of local gages determined that the incidence and severity of ice jam flooding in the region is highly variable and dependent on local river characteristics. This finding is in agreement with the overall understanding of ice-affected flooding in general. However, historical documentation indicates that ice-affected flooding on the Madison River is unique in its general characteristics and severity.

To establish the ice-affected profiles and flood mapping on the Madison River, the ice-affected surcharge was applied to the open water profile modeled in HEC-RAS (**Table 3-5**). The ice-affected surcharges were determined from the adjusted rating curve developed at the gage station. Surcharges were applied through the entire Madison River study from the downstream extent of this study upstream to the cross section at River Station 46,158 (45,274 Feet Above Climbing Arrow Road). The reason for the difference between River Station and Distance Above Climbing Arrow Road is because HEC-RAS River Stationing for the modeled Cross Sections begins at 1,000 for the most downstream Cross Section, which is 110 feet above Climbing Arrow Road bridge. Thus, there is about an 890-foot difference between the model River Stationing and feet above Climbing Arrow Road bridge as indicated on the profiles (see **Appendix H** Hydraulic Analysis Table for cross reference between profile baseline stationing and model cross section stationing). An analysis of the characteristics of the Madison River within this study reach indicated that the characteristics that support the formation of ice jams are present in the lower portions of this study reach, but these characteristics are no longer present (or greatly diminished) upstream of River Station 45,274. Thus, the ice jam surcharge is not applied upstream of River Station 45,274, and the ice jam surcharge was extended as backwater upstream of River Station 45,274 until the water surface elevation matched the modeled open water surface elevation.

Note that the hydraulic modeling results presented in the Modeled Cross Section Geometries (**Appendix G**) represent the open water results of the hydraulic model and do not have the ice jam surcharge included in the output. However, the Hydraulic Analysis Tables (**Appendix H**) and mapped floodplain boundaries presented in the Work Maps (**Appendix B**) represent the Water Surface Elevations and Floodplain extents with the ice jam surcharge applied to the open water model results.

Further detailed discussion of reasoning and defense for this approach are presented in **Appendix L**.

Table 3-5: Madison River Ice-Affected Surcharges

Annual Exceedance Probability	Ice-Affected Surcharge (ft)
10-Percent	2.8
4-Percent	3.9
2-Percent	4.2
1-Percent	4.4
0.2-Percent	4.7
1-Percent 'plus'	4.4

3.16. Calibration - Verification

There are two stream gages in this study area that were utilized to compare model results with gaged data. USGS 06040000 (Madison River near Cameron MT) and USGS 06038800 (Madison River at Kirby Ranch nr Cameron MT) are within this study area. The Cameron gage lies with the 2D South of Ennis analysis area and the Kirby gage is in the upper reaches of the 1D no Floodway analysis area near the top of the study area. Field survey efforts collected reference mark data at these gage sites and were able to tie in the gage datum to real-world coordinates. The table below presents the information used to verify modeled results compared against somewhat recent peak flow values at the gage sites.

For the Kirby gage, a flow rate equal of 5,000 cfs was input as a profile in the 1D hydraulic model as the highest flows for verification and roughly equal to the May 31, 1993 flood event (5,030 cfs) and equal to the June 6, 1986 flood event (5,000 cfs). The stage on the USGS gage for those events were 3.15 ft and 3.14 ft, respectively. Based on gage datum determined from the field survey, the estimated gage water surface elevation for these events was 5,875.94 ft (NAVD88). The hydraulic model results at the nearest modeled cross section (River Station 232,760) is 5,875.64 ft. The difference between the gaged and modeled water surface elevation is -0.3 ft, indicating very good agreement between the hydraulic model and the gaged data.

At the Cameron gage, significant peak flow values of 8,830 cfs (June 11, 1970), 6,670 cfs (June 7, 1952), and 6,600 cfs more recently (June 24, 2011). These flows roughly correspond to modeled flow events in this reach with 10% annual chance (7,050 cfs) and 2% annual chance (9,160 cfs). Resultant water surface elevations taken from the 2D model results for these recurrence intervals were compared against the gaged water surface elevations for the events to determine the degree of agreement between the modeled and gaged results. The field surveyed datum for the Cameron gage is 5,145.66 ft (NAVD88). The stage for the June 11, 1970 event was 5.31 ft, resulting a gaged water surface elevation of 5,150.97 ft. The modeled 2% annual chance water surface elevation at the gage location was approximately 5,151.6 ft, which is approximately 0.6 ft difference. Given the gaged flow event is a little less than the 2% annual chance flood, the difference is less and likely on the order of 0.5 ft. This indicates reasonable agreement between the 2D model results and the gaged water surface elevations for a fairly high flow event. At the lower flows (10% annual chance), the gaged water surface elevations were 4.61 ft and 4.82 for the 1952 event and 2011 event, respectively (Note that the 2011 event had a gage datum changed during the year). Thus, the resulting gaged water surface elevations are 5,150.27 ft (1952) and 5,150.48 ft (2011). The modeled 10% annual chance water surface elevation is approximately 5,151.25 ft. Again, the 10% annual chance discharge is higher than the gaged peak flow values, but provide results that indicate relatively good agreement between the observed gage water surface elevations and those determined by hydraulic modeling in this reach.

Datum Source	USGS 06040000 Madison River near Cameron MT	USGS 06038800 Madison River at Kirby Ranch near Cameron MT
Stream Gage Datum (listed on USGS gage website, ft NAVD88)	5,135	5,860
Stream Gage Datum (field survey, ft NAVD88)	5,145.66	5,872.79

There are no active stream gages within the below Ennis Lake study reach, and the inactive stream gages in this study reach were discontinued more than 100 years ago. No readily identifiable high water marks from recent high flow events were identified in the course of field survey activities or other investigations. Thus, calibration was not performed through in the study reach below Ennis Lake.

4. Floodplain Mapping

FEMA's KSS and many of FEMA's technical guidance documents were consulted to ensure the mapping meets mandatory requirements necessary to map the results of this study on Madison County's and Gallatin County's FIRM panels in the future. To create this data set so that it can be incorporated into the County DFIRMs, the following guidance documents were used: Data Capture Standards Technical Reference (**Reference 16**), FIRM Panel Technical Reference (**Reference 23**), Mapping Base Flood Elevations on Flood Insurance Rate Maps (**Reference 24**); Metadata (**Reference 25**); Physical Map Revision (PMR) (relevant sections; **Reference 26**); Flood Insurance Rate Map (FIRM) Database (**Reference 27**); and, Flood Insurance Rate Map (FIRM) Graphics (**Reference 28**).

In this section of the report the work maps are presented to illustrate the SFHAs in the study.

4.1. Floodplain Work Maps

Floodplain mapping was performed using results from the hydraulic analysis and the 2017 Quantum Spatial LiDAR. The workmaps are included in **Appendix B**, and they show the locations of the 1- and 0.2-percent-annual-chance flood event floodplain delineations along with the floodway delineations. Water surface elevation data, as well as floodway extents, were extracted from HEC-RAS using GeoHECRAS, version 2.7. GeoHECRAS was also used to produce rough floodplain delineations. These rough delineations were manually smoothed and adjusted to ensure reasonable floodplain delineations and to account for hydraulic features such as backwater or islands.

At some hydraulic cross sections, mapped floodplain and floodway topwidths may not exactly match modeled floodplain and floodway topwidths. These apparent discrepancies have multiple causes, depending on the cross section. Some of the common reasons for apparent map-model discrepancy include:

- All small islands are removed from the mapping – this is a standard FEMA practice to account for uncertainty around the islands, and because many islands are not visible at the FIRM scale. Large islands in the floodway where the average ground surface is less than 0.5 foot above the BFE were also not mapped, in order to retain floodway capacity.
- Hydraulically disconnected areas, which occasionally impact the model topwidth, are not mapped
- Mapping at a cross section can be influenced by another flooding source
- Differences can be caused by rapid expansion or contraction of the floodplain width in the model – i.e. – one cross section depicts flow wide across the entire low valley of the floodplain, and the next cross section depicts all flow contained in the channel. However, in reality, all flow would not immediately be directed to the channel. In these instances, engineering judgment was used to create a realistic floodplain.

At many locations, engineering judgment was critical in determining the appropriate floodplain and floodway boundaries.

4.2. Tie-In Locations

No tie-in to effective SFHAs are necessary in this area – there is no effective mapping in the study area to tie into. A concurrent floodplain study is being performed on the reach of the Madison River below this study area as part of the Three Forks, MT floodplain study. Results from the hydraulics analysis on the Three Forks study were utilized to tie this study into the Three Forks study.

5. Flood Insurance Study

FEMA's KSS (**Reference 15**), Technical Reference: FIS Report (**Reference 22**), and Guidance for Flood Risk Analysis and Mapping: Flood Insurance Study Report (**Reference 24**) were followed to create the products in this section of the report. The FIS components included in **Section 4.1** was created using FEMA's latest format specifications.

5.1. FIS Text

The relevant FIS tables have been populated with data from this study. The FIS information is in **Appendix I**.

5.2. Floodway Data Tables

The Floodway Data Tables are in **Appendix J** of this report. Footnotes have been added where appropriate to denote cross sections where special considerations cause differences between the information reported in the Floodway Data Tables, the HEC-RAS model, or the Hydraulic Work Maps.

5.3. Water Surface Elevation Profiles

The water surface elevation profiles depict the 10-, 4-, 2-, 1-, and 0.2-percent annual chance flood events, along with the "1%+" annual chance event are included in **Appendix K** of this report. Two sets of profiles are presented in this Appendix for the below Ennis Lake reach. The first set of profiles represent the "With Levee" scenario results and include the ice jam surcharge as described in report **Section 3.13** and **Section 3.15**. The second set of profiles are presented to reflect the "Without Levee" scenario results (**Section 3.13**), and only include the panels where the levee exists (Panels 01P – 11P). The "Without Levee" profiles also have the ice jam surcharge applied (**Section 3.15**).

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